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NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

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FLIGHT OPERATIONS
FOR
HIGHER HARMONIC CONTROL RESEARCH

by

James Joseph McGovern

March, 1991

Thesis Advisor:

E. Roberts Wood

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Flight Operations
For
Higher Harmonic Control Research

by

James Joseph McGovern
Lieutenant, United States Navy
B.S., United States Naval Academy, 1983

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

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March 1991

ABSTRACT

The Department of Aeronautics and Astronautics at the Naval Postgraduate School (NPS) is interested in extending the useful life of Naval helicopters. Recognizing the need to reduce vibrations caused by aerodynamic loads on the rotor system, a Higher Harmonic Control (HHC) research effort has begun. The test vehicle of the HHC system is a Remotely Piloted Helicopter (RPH). This thesis contains an overview of the NPS HHC research effort including basic helicopter dynamics, HHC theory, and establishes research milestones. An RPH flight operations program was developed that included the first flights of two out of three RPH's being used in the research effort, identification of data and data acquisition requirements, and initial hover vibration tests. The vibration tests produced data of limited value. The two bladed RPH tested appears to produce peak accelerations at roughly twice the main rotor speed. This indicates that like a full scale helicopter, the largest vibrations do enter the airframe through the rotor system and are not a result of engine vibrations. Hence, RPH's are suitable for HHC research. This effort completed one portion of the long term HHC research and can lead to the practical and safe testing of a fully functioning HHC system.

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Lastly, to Dr. E. Roberts Wood for not only championing helicopter research at NPS but also for passing on a small part of his vast knowledge of helicopters and helicopter systems. To each of you and those not specifically mentioned, thank you.

I. BACKGROUND

A. HELICOPTER VIBRATION

The increasing cost of aircraft development and production is driving the need to increase the useful life of modern aircraft. Structural fatigue is the largest contributor to low airframe life in helicopters. Increased crew comfort and decreased structural fatigue can be achieved by limiting vibrations.

In recent years, helicopter vibration levels have decreased as noted at an American Helicopter Society (AHS) specialists' meeting on helicopter vibrations in 1981 [Ref. 1]. Figure 1 compares achieved and predicted achievable levels of vibration to the industry-wide criteria for a "Jet Smooth Ride." Additionally, the United States Army's Utility Tactical Transport Aircraft System (UTTAS) Request For Proposal (RFP) criteria are displayed. It is noteworthy to point out that the UTTAS vibration criteria were revised when it was determined the maximum vibration levels of 0.05g, though possible, added too much weight, cost, and complexity to the aircraft. It was during this time that considerable research to design active vibration devices was begun.

Helicopters, because of their many rotating components, often have high levels of vibration. Generally, vibration can be divided into two categories, ordinary and self-excited [Ref. 2].

Self-excited vibrations are those not requiring external stimuli to sustain the vibration. For instance, ground resonance is a result of the coupling of the blade lag motion and the motion (fore and aft or sideward) of the rotor shaft. The occurrence of ground resonance, like most self-excited vibrations, can be eliminated through good design.

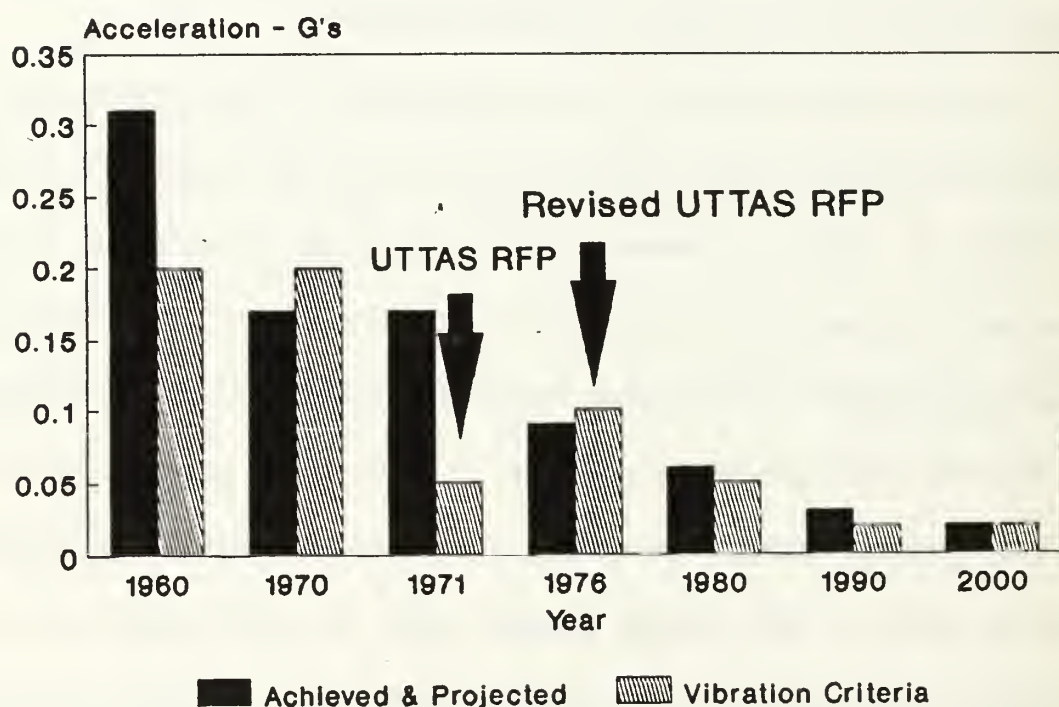


Figure 1. The Ride Revolution

Ordinary vibrations are due to excitation by an external force such as the aerodynamic forces acting on the rotor blades and fuselage. Obviously, the

aerodynamic forces cannot be eliminated. Thus, the resulting vibration must be maintained at manageable levels.

The most common method of dealing with helicopter vibration has been through the use of passive vibration devices such as absorbers and dampers. A good example of a damper would be the oleo strut in landing gear, or the lead-lag damper for an articulated rotor blade. Absorbers can be found throughout a helicopter, the simplest being rubber shock isolation mounts, typically for individual pieces of electronic equipment.

B. VIBRATION REDUCTION

1. Passive Techniques

Passive vibration reduction, though useful, is limited. The effectiveness of absorbers and dampers is limited by the fact that they are designed to reduce a particular frequency vibration. And, when operating off the design frequency they can actually increase the amplitude of the vibration. The durability of machinery such as turboshaft engines and pumps operating at a constant frequency can be enhanced by one of these devices. The design penalties are increased complexity, weight, and cost.

An absorber can be easily modeled by a mass-spring system as shown in Figure 2. The smaller second mass can be installed on a spring-like mount such that the net displacement of the system is zero. The energy the absorber receives is dissipated by vibrating itself rather than allowing the system to vibrate.

Dampers can be similarly modeled using a spring-mass-dashpot system like the one in Figure 3. The dashpot device provides viscous damping. Any motion between the piston rod and the cylinder is resisted because the oil in the cylinder must flow around the piston. This dashpot, or damper, absorbs energy which is dissipated in the form of heat rather than displacement or vibration [Ref. 3].

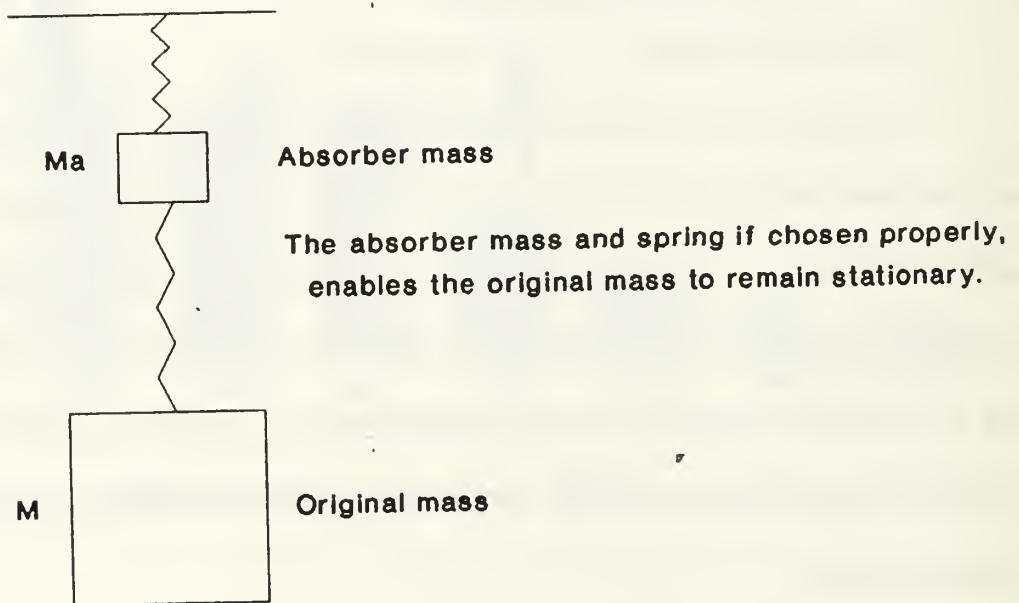


Figure 2. Spring Mass System

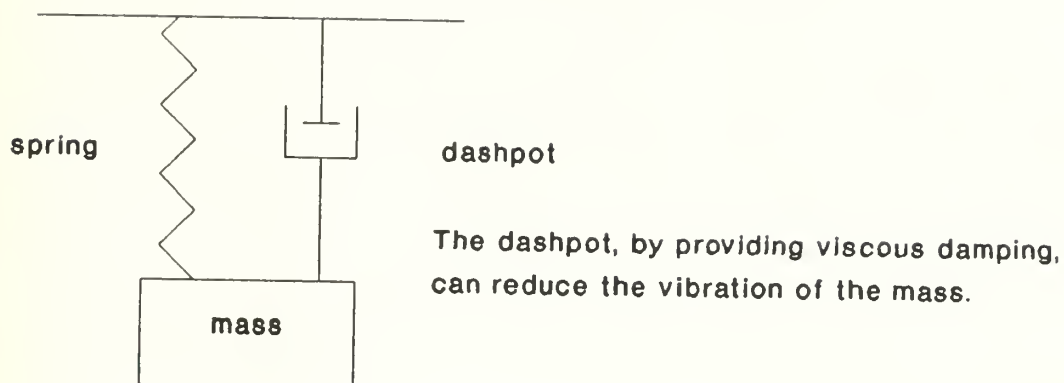


Figure 3. Spring Mass Dashpot System

2. Active Techniques

Vibration reduction of aerodynamic loads by passive techniques treats the vibratory loads after they have been generated. Passive techniques are very restricted because the magnitude and frequency of these vibrations vary with the load exerted on the rotor system as well as the airspeed of the airframe. In order to reduce these variable loads, an active device is more desirable. An active device

is one that alters the vibratory excitation, such as unsteady aerodynamic loads, preferably at the source.

Higher Harmonic Control (HHC) is a technique where the vibrational loads transmitted to an airframe by the aerodynamic forces imparted on the rotor system are measured and, a diametric load is then imparted back into the rotor system to reduce or cancel the effect of the initial vibration. By actively measuring the vibration and responding, the vibration can be reduced over a range of frequencies or flight conditions. Additionally, the structural fatigue of the airframe can be reduced since the vibratory loads are eliminated at the rotor system and do not enter the airframe.

II. SCOPE

The Department of Aeronautics and Astronautics at the Naval Postgraduate School (NPS) is interested in research that can lead to extending the useful life of Naval helicopters. Recognizing the need to reduce the effect of vibrations caused by aerodynamic forces, an HHC research effort has begun at NPS.

In order to test the feasibility of HHC, the theory needs to be fully developed. Additionally, a working HHC system has to be designed, built and tested. However, before producing an HHC system, considerable project development has to be done. It has been recognized that by utilizing a remotely-piloted helicopter (RPH) useful data could be obtained without the high cost and risk associated with full scale helicopter testing. The NPS Unmanned Air Vehicle (UAV) Flight Research Laboratory has provided vital elements in this effort.

The scope of this master's project is to develop an HHC flight program that will lead to practical and safe testing of a fully functioning HHC system on an RPH. To this end, basic helicopter dynamics were researched and applied to HHC theory. Requirements for data gathering were ascertained and from that equipment needs determined. Basic elements of a safe and an effective RPH flight program have been learned. Hover test procedures have been developed that will facilitate vibration testing of HHC modified helicopters as well as for other research.

III. HIGHER HARMONIC CONTROL

A. HELICOPTER DYNAMICS

Dynamics is the study of the relationship between motion and the forces effecting motion. The relationship considered here, is the interaction between loads on helicopter rotor systems and the resulting motion of the airframe. A basic understanding of helicopter flight controls is necessary in order to understand where the loads come from and how they are transmitted into the airframe. Figure 4 [Ref. 2] depicts a conventional helicopter control system. The upper swashplate, its connecting control links to the rotor hub, the rotor hub and rotor blades all rotate with the main rotor shaft. The lower swashplate and its control linkages are non-rotating. The swashplates are commonly called the rotating swashplate and the stationary swashplate, respectively.

The fuselage vibration resulting from the rotor blade vibratory response to aerodynamic loads is significant. The rotor blades are restrained at the root, which leads to shear loads and moments at the blade roots and rotor hub as a result of aerodynamic loads. The shear forces are broken into vertical shear, S_z , and in-plane shear, S_x and S_y . These forces are transmitted through the rotating control system to the stationary system, and ultimately to the fuselage and its components. The moments take the form of a flapwise moment, N_F , and a lagwise moment, N_L . An

articulated rotor system is one that is hinged in the flapwise and lead-lag directions. On an articulated rotor the flapwise and lagwise moments are zero or small [Ref. 4].

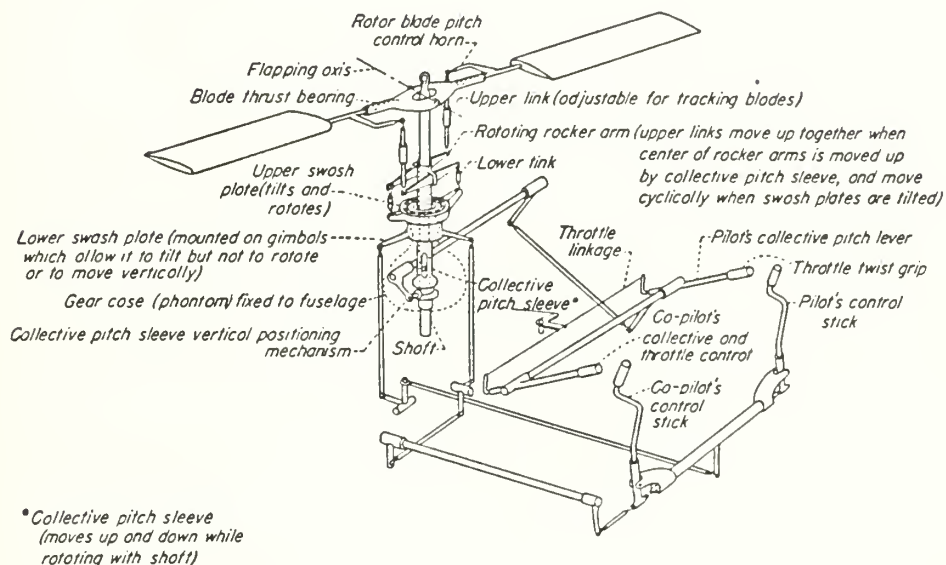


Figure 4. Conventional Helicopter Control System

The forces and moments that the rotor hub experiences are periodic, because at a given position in a rotor revolution each blade experiences identical loading. As the shear forces are transmitted from the rotating system to the fixed system the rotor acts as a filter. For an n -bladed rotor system the most troublesome frequencies

allowed through to the fixed system are the n per revolution (n/rev) and $2n$ per revolution. Since the lower harmonics of blade loading are of greater magnitude, the n/rev vibration of the fuselage is most crucial. To understand how the forces are transmitted to the fixed system and in what form they appear, consider a simple example as shown in Figure 5 [Ref. 5].

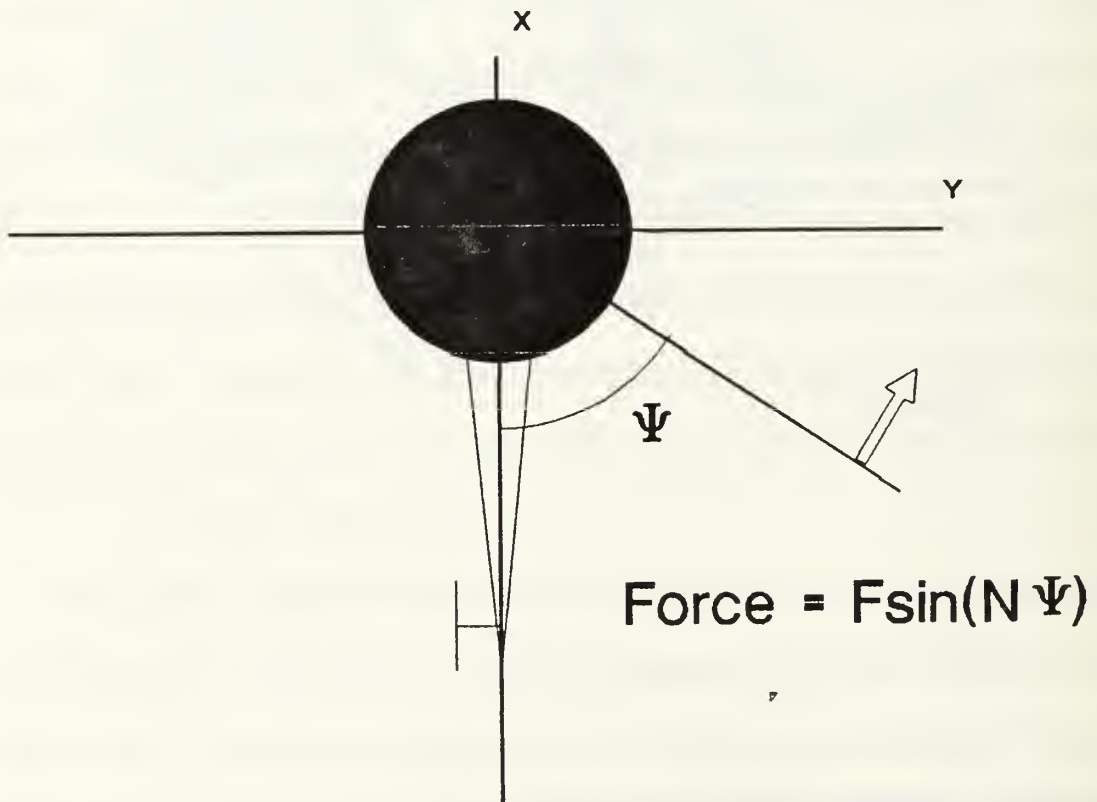


Figure 5. Filtering of Rotor Forces

The in-plane vibratory force, $F \sin(N\psi)$, in the rotating system results in excitation on the fixed system at $(N+1)\psi$ and $(N-1)\psi$. This is clearly seen by breaking the in-plane force into its X and Y components as shown below:

$$F_x = F \sin(N\psi) \sin(\psi)$$

$$F_x = \frac{F}{2} \cos(N-1)\psi - \frac{F}{2} \cos(N+1)\psi$$

Similar analysis is used for out-of-plane forces and moments.

Summarizing, for an n-bladed rotor in steady-state flight, forces at frequencies of n/rev that are filtered into the fixed system are a result of vibratory forces at the rotor blade root of n-1/rev, n/rev, and n+1/rev. The filtered forces and moments take on the following form:

- n/rev vertical forces and moments are transmitted to the fixed system at a frequency of n/rev.
- (n-1)/rev and (n+1)/rev in plane forces and moments are transmitted to the fixed system at a frequency of n/rev.

Specifically, the n/rev S_z and N_L generate n/rev thrust and torque, the (n-1)/rev and (n+1)/rev S_x and S_y generate n/rev drag and side force, and the (n-1)/rev and (n+1)/rev N_F generate n/rev pitch and roll [Ref. 4].

B. HHC THEORY

HHC is an electronic means of actively reducing vibrations.

The aerodynamic forces that impinge on the rotor blades causing fuselage vibration can be controlled by understanding helicopter dynamics and applying HHC techniques. From helicopter dynamics, the source and periodicity of fuselage vibration are understood. The goal of HHC is to make blade pitch change inputs such that the forces and moments filtered through the rotor system are damped before they reach the fuselage.

The rotor system is capable of filtering from the fixed system to rotating system as well as from rotating to fixed. HHC inputs will be made to the fixed system and filtered to the rotating system. The control linkages, actuators that connect the pilot's control inputs to the stationary swashplate, will be excited by HHC at n/rev . This excitation yields blade pitch oscillations of $(n-1)/\text{rev}$, n/rev , and $(n+1)/\text{rev}$. Normal control inputs through the cyclic pitch control result in $1/\text{rev}$ blade pitch changes.

HHC inputs are a result of measured and predicted aerodynamic loads. Inputs can be made using an open loop or closed loop HHC system. Open loop control has no feedback; thus the phase and amplitude of the actuator input must be made manually. Closed loop control employs feedback of airframe vibration through an onboard computer to automatically adjust the actuator input. Among the closed loop HHC systems the feedback can employ a fixed-gain control law or an adaptive control law.

Obviously, HHC can manifest itself in many ways, but each system operates on the same principles and each system contains the same basic components. The primary elements or components of a working HHC system are [Ref. 6]:

- Acceleration Transducers
- Onboard Microcomputer
- Signal Conditioning Unit
- HHC Blade Pitch Actuator System

Each of these components is a sub-system of HHC; hence, design choices must be made for each, keeping in mind that ultimately these sub-systems must be compatible.

C. HHC RESEARCH EFFORT

1. Goals

In order to extend aircraft service life, its research goal, NPS when developing an HHC program had to develop many intermediate goals. These milestones must be chosen to work congruently; however, flexibility must be present to ensure continuous progress as well as allowing NPS to seize research opportunities as they arise.

The idea of extending the service life of a helicopter airframe is by no means new. The increased costs associated with the design and development of new

platforms has manifested itself in an aging inventory as shown in Figure 6 [Ref. 7]. The weight penalty and inherent limitations of passive vibration devices led to the decision to study active vibration reduction.

AVERAGE FLEET AIRCRAFT AGE (1973-1995)

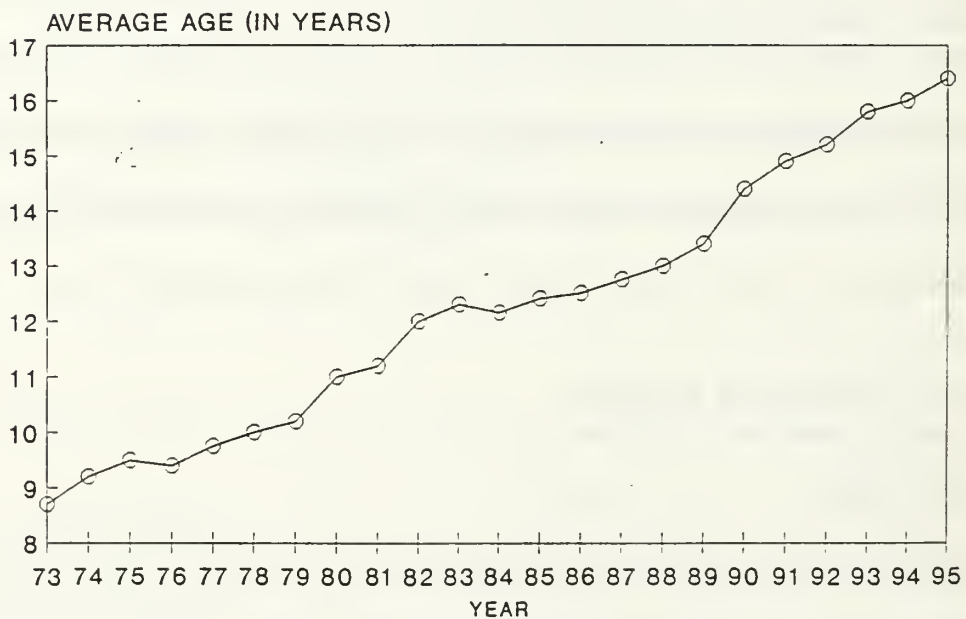


Figure 6.

2. HHC Flight Testing

A considerable amount of theoretical work has been accomplished, but to date little verification of the theory has been done. The NPS program has placed the highest priority on flight testing an HHC system. Specifically, it is being developed to determine if and how much HHC reduces vibrations and if HHC has other practical benefits like performance enhancement and a lower noise signature. Hughes Helicopters Incorporated did the most notable concept verification to date, which resulted in the first successful flight tests of a HHC modified helicopter (U.S. Army OH-6A) [Ref. 6].

3. Remotely Piloted Helicopters

Model helicopters are being used in NPS research for numerous reasons, including low cost, maintainability, and safety. Finding and procuring an appropriate model was a major milestone. A four-bladed main rotor system was chosen because 3/rev, 4/rev and 5/rev do not interfere with the primary 1/rev control inputs. The RPH chosen had to have enough power for basic flight performance while supporting its own weight, as well as the HHC system and data acquisition system. The RPH chosen was produced by Pacific RPV and is called the *Bruiser*, shown in Figure 7 [Ref. 4].

4. RPH Support Facilities

The UAV Flight Research Laboratory has demonstrated the practicality of using radio controlled aircraft for flight testing. Development of the RPH flight test

program has been enhanced because of the previous successes at the UAV Laboratory. The facilities have been modified to provide support for an RPH program with several helicopters and research projects. The "in-house" knowledge allowed many immediate successes without the usual trial and error associated with new programs.

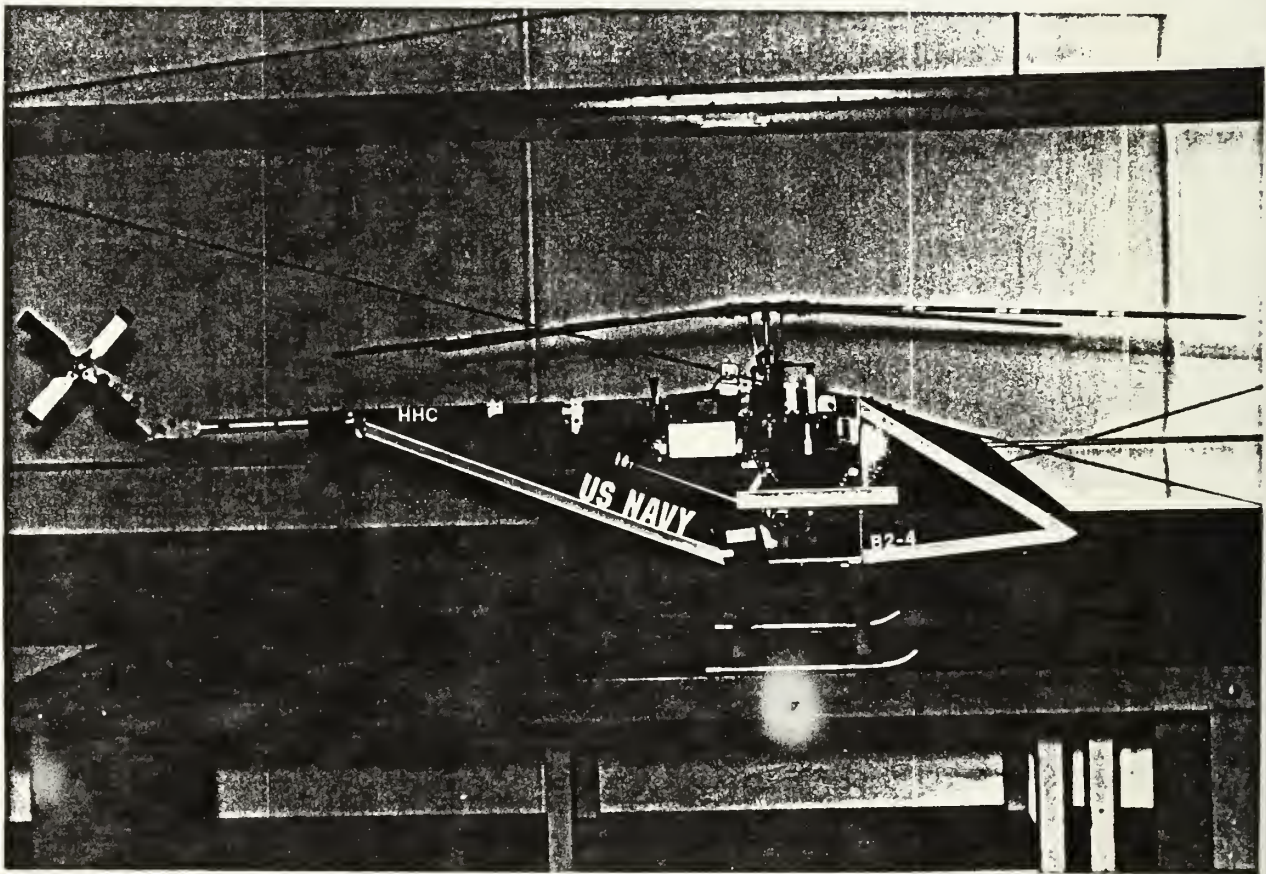


Figure 7. Pacific RPV Bruiser

5. Data Gathering

Any flight test program aspires to obtain useful data. Before these flight tests are conducted, data requirements must be determined along with realistically assessing data acquisition ability. The Hughes Helicopters OH-6A had an Airborne Data Acquisition System (ADAS) capable of accepting 72 channels of analog, digital, and audio signals. Some of the things the ADAS measured and recorded were blade bending, pitch link loads, fuselage loads, and fuselage vibrations [Ref. 8]. On an RPH, data gathering will be much more limited due to the size of the useful load. The initial NPS flight tests will seek aircraft performance data such as airspeed and rotor speed as well as airframe vibration levels. In addition, it is hoped to monitor such parameters as actuator output motion and phase. This will allow proof of concept as well as some quantification of the theoretical benefits of HHC.

6. Flight Tests

The flight test program includes the following phases. Initially, flight tests will be conducted to de-bug the data gathering system. The first flight tests will be "hover only" flights using an accelerometer tethered by coaxial cable to an acceptable display and recorder. From that data the suitability of the accelerometer as well as system noise will be determined. Following that, a telemetric data acquisition system or self-contained onboard recorder will be built, tested and installed. The next flight tests will try to establish baseline vibration values that the HHC-modified helicopter can use for reference. Baseline flights will include both hover and forward flight. Accurate baseline data from an unmodified RPH will be essential to evaluate the

HHC-modified RPH. The final portion of the RPH HHC tests will be to compare HHC-on verses HHC-off vibration and performance in a comprehensive open-loop flight test program. This program will be designed to first explore level flight steady-state conditions. Following that, selected maneuver transients, such as pull ups and wind-up turns, will be investigated.

IV. RPH PROGRAM MILESTONES

A. PREPARATION FOR FLIGHT

Procurement of the *Bruiser* was the starting point in preparation for HHC RPH research. Once the *Bruiser* reached NPS the project could be worked from two directions: first, the design and building of an HHC system for the RPH and second, the preparation for flight testing. The *Bruiser's* high value, both in terms of initial cost and in terms of research effort expended, resulted in the need for a carefully planned flight program.

Obtaining the services of a qualified pilot was the first objective of this phase of the research effort. The UAV Laboratory Technician, Don Meeks, proved to be a logical choice. Although he did not have RPH flight experience, his 30 years of fixed wing radio controlled experience provided a solid foundation on which RPH skills could be built. Additionally, Mr. Meeks can supply continuity to the research program considering the fact that a student participates in the program for a relatively short time.

The pilot's affiliation with numerous modeling clubs allowed him to find another modeler, Dennis King, who had RPH experience and was willing to help get the NPS program off the ground. The knowledge and recommendations of these two qualified pilots coupled with other "in house" experience and the facilities of the UAV Laboratory allowed the flight test program to proceed.

B. SAFETY

The first concern of any flight test program must be how to make progress in the research area safely. Considering the high cost of the *Bruiser* and the limited RPH experience of our pilot, there was a need for considerable training.

The sophistication and features of the unmodified *Bruiser* drove its cost to nearly \$10,000 and a modified *Bruiser* is projected to cost about \$50,000. Flying such an RPH is not a task to be performed by a novice and a minor mishap could be very costly in terms of lost research effort as well as money. So, pilot training was accomplished through the utilization of two intermediate size RPH's, shown with the *Bruiser* in figure 8., rather than a costly research platform. The first RPH was a Schuler *Heli-Star* and the second RPH a GMP *Legend*.

C. HOVER

Before free flight can be attempted, hover skills must be mastered. Due to the lack of experience, a tethered hover was essential to prevent a mishap early in the program. The idea behind the tethered hover was to provide the pilot with some feel of control inputs without the risk of damaging the helicopter. Once the pilot felt comfortable with how the RPH responded to a given input, an unrestrained hover was attempted, practiced, and eventually mastered.

D. FREE FLIGHT

This portion of the flight training is on-going and can only be done after having spent hours practicing hover techniques. The difficulty of this portion is two-fold. First, once the RPH leaves the vicinity of the pilot,

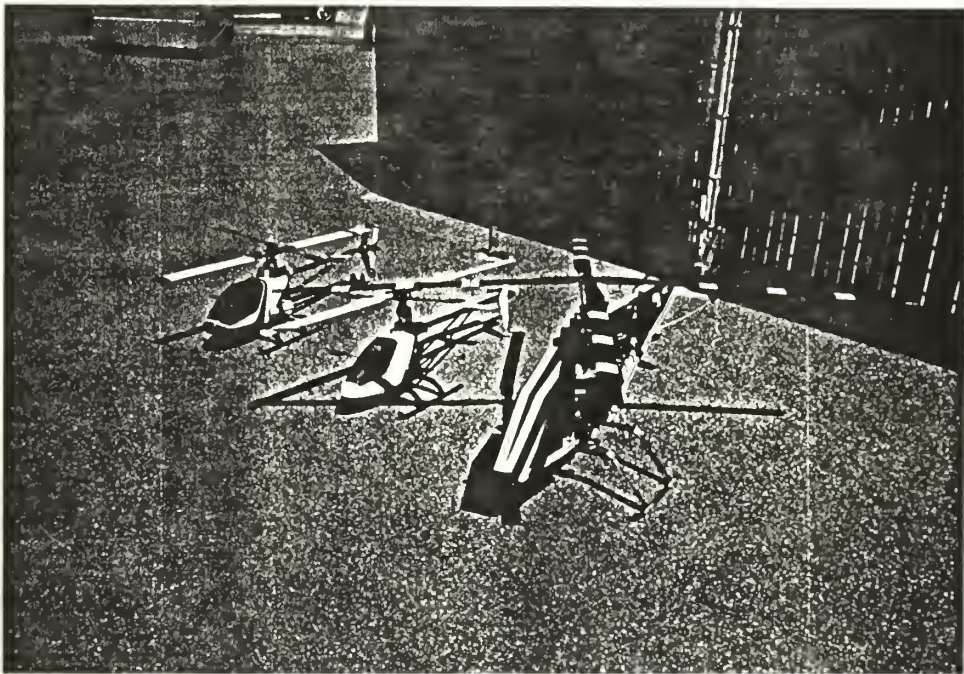


Figure 8. Heli Star, Legend, and Bruiser

picking up visual cues with respect to the RPH's attitude and orientation can become fatiguing. The paint scheme on the RPH can be invaluable in providing the necessary cues. The *Heli-Star* was painted white and fluorescent orange like the

aircraft used at the Naval Air Test Center, Patuxent River, Maryland. Second, it can be quite disorienting when the RPH is flying toward the pilot. The only way to combat this is through training the pilot to mentally put himself in the RPH. By doing this he can avert the feeling that he is using opposite controls when the RPH is flying toward him.

E. HOVERING FLIGHT TESTS

Hover performance testing is difficult with a full scale helicopter and even more with an RPH. The goal of the NPS program is to attempt quantification of the most basic performance data, power required to hover and vibration levels. Since helicopter power required is usually near its maximum in a hover, this is a logical flight regime to test helicopter performance. By accurately measuring power required to hover, it can be determined if HHC enhances performance. RPH vibration data will also be measured in the hover tests. By establishing this capability, future research not necessarily associated with HHC can also be performed on the NPS RPH assets.

F. FORWARD FLIGHT TESTS

Forward flight tests are the end goal of the flight testing portion of the HHC research effort. A major limitation of this portion will be the payload available on the RPH for data acquisition equipment. Because of this limitation a telemetry

system may have to be used rather than having flight data recorders onboard. RPH vibration levels will be quantified during forward flight tests at various airspeeds and rotor loads.

V. FLIGHT OPERATIONS

A. *Heli-Star*

1. Application

In 1985 NPS obtained an RPH to examine the relationship between model helicopters and full-size helicopters. It was noted that the similarities between the model and full-size helicopter outnumber the differences. However, it was concluded that the RPH could not easily be used for college or university level research for two reasons: the current data gathering instrumentation was too large or too expensive for use on a model, and the lack of pilot proficiency gave rise to safety concerns [Ref. 9].

Next a study of hover performance and the utility of using the *Heli-Star* as a training aid for classroom presentation was conducted. From this research, it was concluded that flight research could be performed using a model helicopter but due to the complexity of the RPH, reliability was a limiting factor. Also, this complexity limited the utility of the RPH in the academic environment [Ref. 10].

After 1986 the *Heli-Star* was not used at NPS until the HHC research effort was begun. Careful consideration was given to the conclusions and recommendations of the previous RPH research. After considering the complexity of the HHC system it was concluded that an RPH was not too complex of a platform to be used for this research. Pilot proficiency was previously a problem area in using RPH's for

research. Utilizing the *Heli-Star* for pilot training and proficiency flying has helped alleviate the problem.

2. Training Device

The *Heli-Star* had fallen into disrepair from lack of use and the feasibility of making it an asset of the RPH program was not known. By making it operational it could be used as a "beginner" helicopter to train our RPH pilot. And, the *Heli-Star* could provide practical data on how much and how difficult maintenance would be on an RPH.

After removing and cleaning the carburetor as well as replacing the radio receiver battery pack the *Heli-Star* started but ran roughly and demonstrated unacceptably high vibration levels. The engine was removed from the helicopter and the shaft re-aligned to within 0.001 inches even though only 0.003 inches is required. Because of the substantial disassembly required to remove the engine, a thorough maintenance was performed on the RPH. During maintenance, it was discovered the tail-rotor blades on the *Heli-Star* were not a matched pair: one used a symmetric airfoil and the other a cambered airfoil. Obviously this was a major contributor to the vibration and the blades were replaced. Lastly, the controls and blade tracking were adjusted through the tedious procedure of starting the helicopter, trimming it, shut it down, make necessary corrections to adjust out the trim, and beginning again. After several iterations a relatively smooth helicopter flew with an experienced RPH pilot at the controls.

The experienced RPH pilot, Dennis King, began instructing the UAV Lab Technician, Don Meeks, how to fly RPH's using the *Heli-Star*. A number of different hover training stands and techniques were used during this phase of the training and will be discussed later.

Maintenance time on the *Heli-Star* has been substantial though it appears to be decreasing as more problems are exercised out of the *Heli-Star* through its use. Approximately fifty hours of maintenance were required to return the *Heli-Star* to flying status. Now, it requires about three hours of maintenance per flight hour.

The proficiency training of our pilot is on-going and using the *Heli-Star* has proven to be effective. This proficiency can be seen not only in the smoothness of helicopter control but also in the improved availability of the *Heli-Star*.

In addition to piloting skills, the experience gained during this process led to the development and use of a checklist system. The checklists are contained in Appendix A. The checklists are both RPH operations checklists as well as functional checklists. The functional checklists such as the Pack-Up checklist ensures that certain tools are brought to the test site to conduct field repairs and that required data gathering equipment will be on hand when needed. This system was developed with safety and efficiency in mind.

3. Hover Performance

References 9 and 10 discussed hover performance testing using the *Heli-Star*, and examined various methods. All the methods had severe limitations, mostly due to complexity. It was pointed out that pilot proficiency had not reached a point

where a tethered hover could produce useable performance data because precision hovering was required. Hence, the research was directed toward design of a thrust stand. The thrust stand used provided little useful data because the RPH, being rigidly attached to the stand, transmitted unacceptably high levels of vibration to the load cell [Ref. 10]. A conventional load cell proved to be inadequate because of these high frequency vibrations and the potential to overload the load cell. Another problem noted was that if the thrust vector was not directly over the thrust stand shaft, a moment was induced that could prevent the free movement of the shaft thereby producing erroneous data.

Rather than try to improve the design of the hover stand and acquire better equipment, improved pilot proficiency has been the aim of the HHC flight test program. It is believed that in this instance the more basic the test apparatus used the more likely the program is to produce accurate results.

B. INTERMEDIATE RANGE RPH

1. Intermediate Requirements

When the need for a pilot training RPH emerged, it was unclear if the *Heli-Star* could economically be made operational and if operational, would it be a suitable training aid. Considering this, the decision was made to pursue acquisition of another RPH while working on the *Heli-Star*.

The intermediate RPH could, if appropriately chosen, serve as both a research platform as well as another training device. A second training RPH was clearly not

necessary; yet, there remains a large sophistication gap between the *Heli-Star* and the *Bruiser*. The typical difference was that one servo on the *Heli-Star* simultaneously controls the throttle and collective as opposed to the *Bruiser*, which has a servo for each control function. The significance of this was, the *Bruiser* can set a rotor speed with the throttle and vary blade pitch for vertical flight like a modern full size helicopter and the *Heli-Star* cannot. The radio purchased for use with the intermediate level RPH is a programmable nine channel radio and, unlike the *Heli-Star* radio, has electronic trim which is used to fine tune the RPH's control settings. The advantage of this is that control adjustments can be made without having to shutdown the helicopter for each adjustment, as was done for the *Heli-Star*.

Careful selection of an intermediate level RPH simplified the transition from *Heli-Star* to *Bruiser* flight operations. And more importantly, an RPH with separate collective and throttle controls typically has a much larger useful payload than one without separate controls. For example, the table below contains specifications for two RPH's: the GMP *Rebel*, a beginner RPH without separate collective and throttle; and the GMP *Legend*, the RPH eventually chosen.

The ultimate justification for the intermediate RPH came from the enhanced useful load of the *Legend*, and the belief that it could not only serve as a research platform but also as a training helicopter.

Table I. Rebel and Legend Specifications

	Rebel	Legend
Rotor Dia.	42"	58"
Tail Rotor	10"	10"
Length	42"	51"
Weight	6.0 lbs	8.8 lbs
Payload	1.5 lbs	10.0 lbs
Engine	.46 cu in	.61 cu in

2. Data Acquisition Platform

Before baseline vibration data is recorded on the *Bruiser*, a data acquisition system must be designed, built, and tested. As previously mentioned, the *Heli-Star* lacks separate collective and throttle control thereby limiting its useful load. The *Heli-Star* is not capable of carrying a data acquisition system and the *Bruiser* is considered too valuable a test platform to be used for de-bugging a data acquisition system.

The GMP *Legend* was purchased and built with this in mind. With a useful load of nearly ten pounds and a control system much like the *Bruiser*, it is serving as a test bed for the data gathering equipment.

3. Future Research Vehicle

After the data gathering equipment is made operational and procedures for hover performance testing refined, the *Legend*, because of its substantial payload, can be used as a research platform for projects other than HHC.

Testing various main rotor blade designs for enhanced vertical lift and retreating blade stall characteristics can be performed using the assets and equipment being developed for the HHC research program. Another research program could easily be undertaken studying different tail rotor configurations. The *Legend* has a belt driven tail rotor and the tail rotor drive system is mounted in an octagon shaped tail boom. Because of this setup, alteration of the current drive is relatively simple. Testing of not only pusher versus tractor configurations but also of various angled drives can be accomplished.

C. RPH FLIGHT TRAINING

1. Ground School

After the *Heli-Star* was made flight worthy and during construction of the *Legend*, an aggressive flight training program was begun. The program was intended to slowly yet deliberately work toward accident free forward flight. The first phase of the flight training consisted of "ground school" much like any flight program. Our pilot had considerable experience with fixed-wing radio controlled operations which allowed the job to go smoothly. The effect of each flight control input was discussed

by examining the swashplate assembly and noting how it effected blade incidence. This was done using the RPH radio and servo mechanisms without the engine operating or rotor turning at a high speed.

The torque produced by the main rotor head and how it affects the fuselage were discussed at length. Understanding the "torque effects" is the key to understanding how the tail rotor works as an anti-torque device. The concept of over-compensating and under-compensating for the main rotor torque in order to turn the RPH is relatively simple and will suffice for normal operations. However, a true working knowledge of how this torque can be used, may help the pilot return the RPH safely if he experiences a partial loss of tail rotor authority.

2. Hovering

Considering our lack of experience and based on the recommendations of a few RPH modelers, the first phase of the flight program consisted of a tethered hover. This was done using the "Flight Master", a three dimensional helicopter flight simulator, shown in Figure 9. Two plastic tie wraps were used initially to restrain the stand allowing the RPH only motion in yaw, seen in Figure 10. Once the pilot became accustomed to rudder control inputs and resulting yaw, one tie wrap was removed. Now the pilot had freedom to both yaw the RPH and raise and lower it, practicing torque compensation presented in Figure 11. Eventually both of the plastic tie wraps were removed and the RPH, though tethered, had freedom to move in any direction, thus allowing further pilot training with low risk to the RPH.

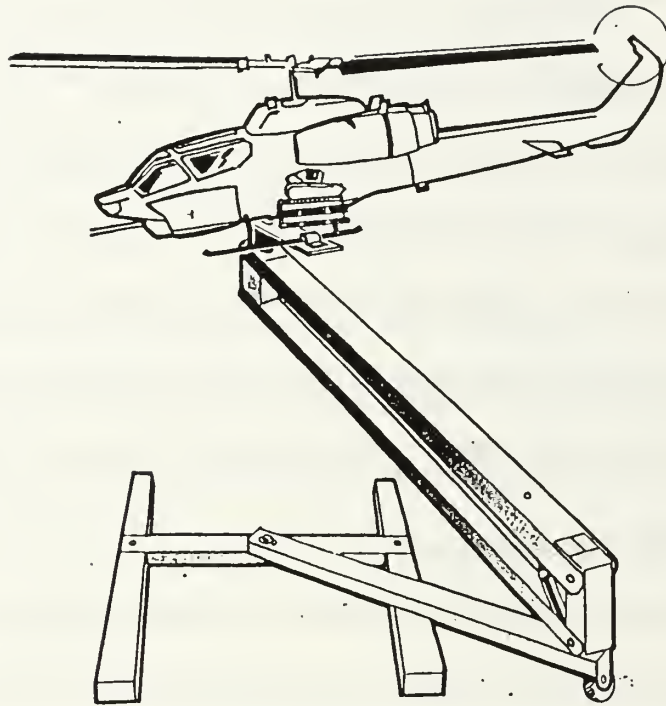


Figure 9. Helicopter Flight Simulator

The next step in the flight program proved to be the most effective in the training program. Training wheels for the RPH were constructed from 3.5 inch plastic balls and five-eighths inch wooden dowels, seen in Figure 12. This X-shaped device shown in Figure 13. was attached to the landing gear of the *Heli-Star* with

rubber bands. This type of training aid provided a broader more stable base for RPH landings, reducing the chance of a tip-over mishap. The training wheels did not

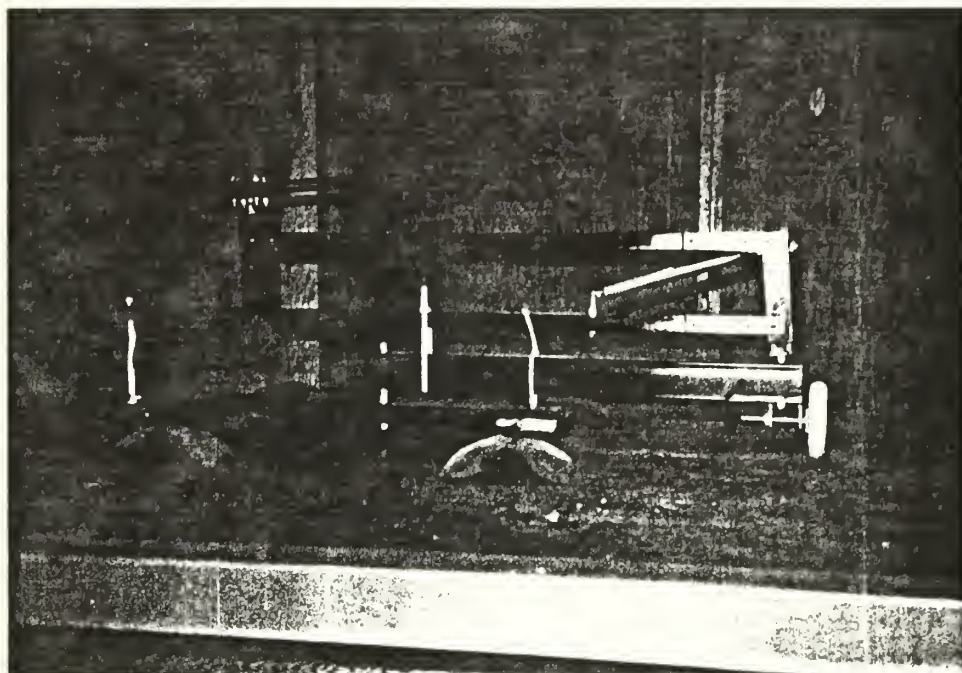


Figure 10. Flight Master, Yaw Motion

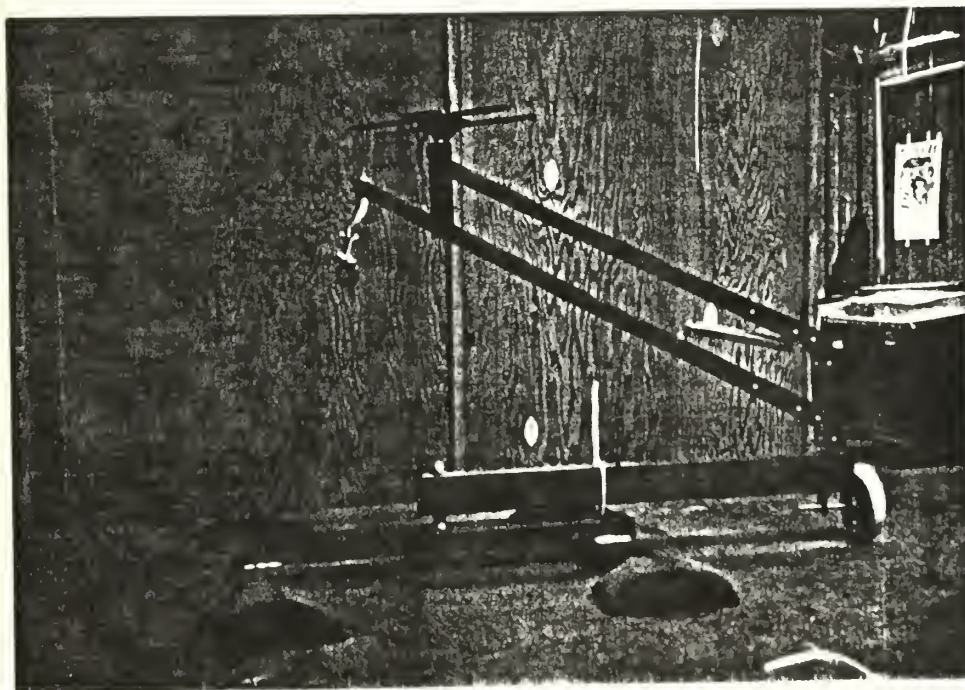


Figure 11. Flight Master, Yaw and Collective

restrict the RPH freedom of movement, allowing the pilot to gain more "feel" for control input and its response to the RPH.

Many hours of flight time were expended using this device. Initially, entire flights were spent on the ground, trying to stay in one location while increasing power enough to get "light on the skids." Then hovers of short duration became longer and landings more controlled.

3. Forward Flight

As hovers became longer and more deliberate, small box patterns were flown to expand the pilot's envelope. The box patterns can be flown maintaining a constant heading or by making a 90 degree turn at each corner of the box keeping the aircraft nose in the box as shown in Figure 14. The purpose behind the box patterns was to increase the pilot's control and precision. The flight envelope was eventually expanded to include forward flight at various airspeeds and altitudes.

Successful flight operations require practice and patience. The RPH pilot must maintain proficiency in flying, and that means he cannot just fly when there are tests to be conducted and data to be recorded. Patience is also a necessity because the weather, high and gusting winds, can force cancellation of flight operations scheduled for proficiency training or data gathering.

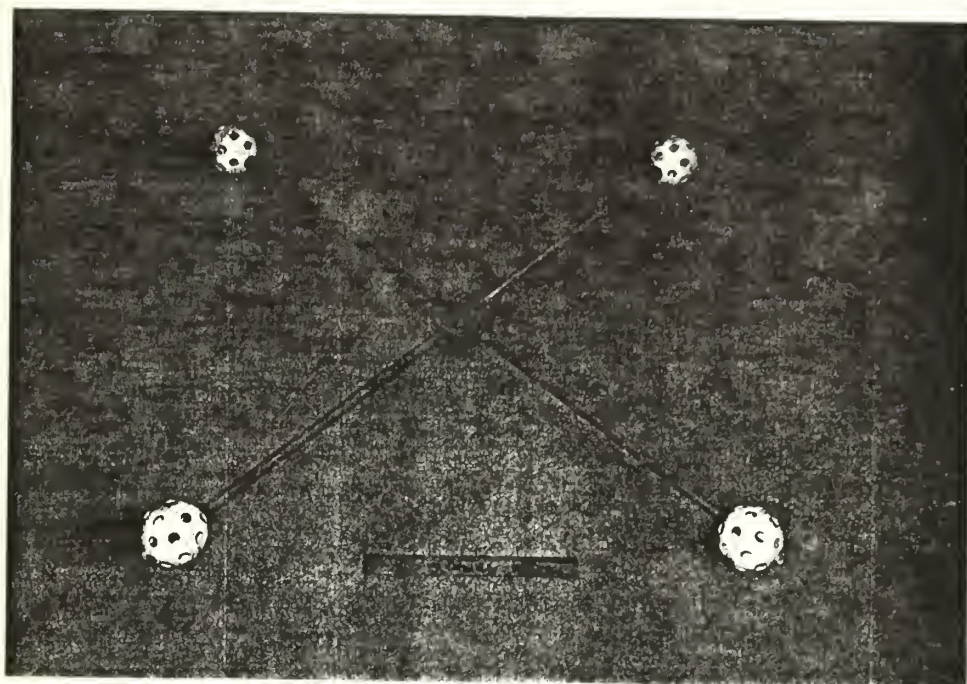


Figure 12. Training Wheels

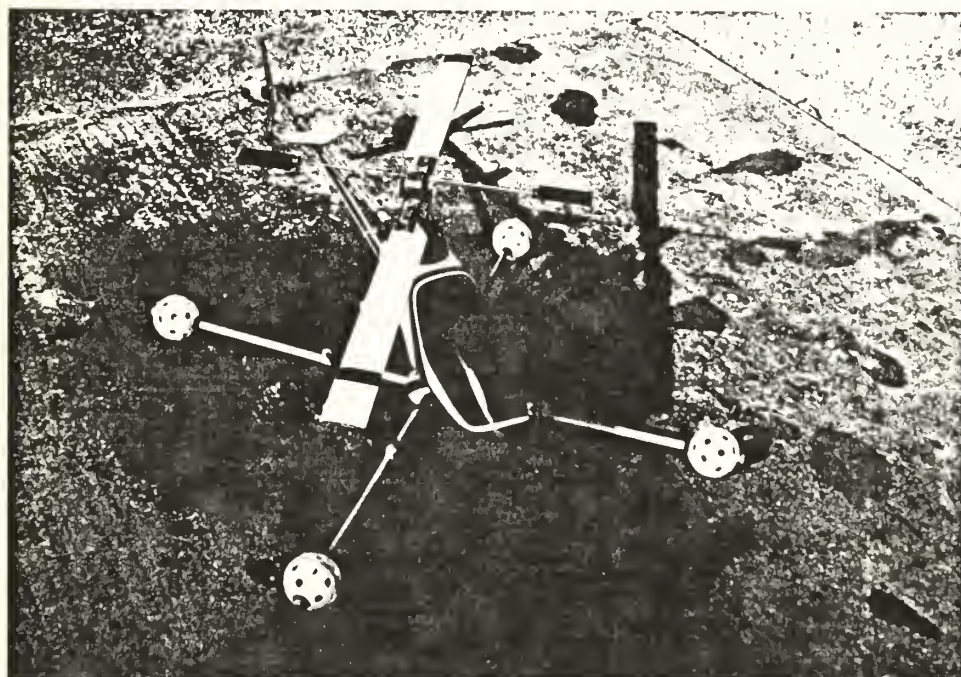


Figure 13. Heli Star with Training Wheels

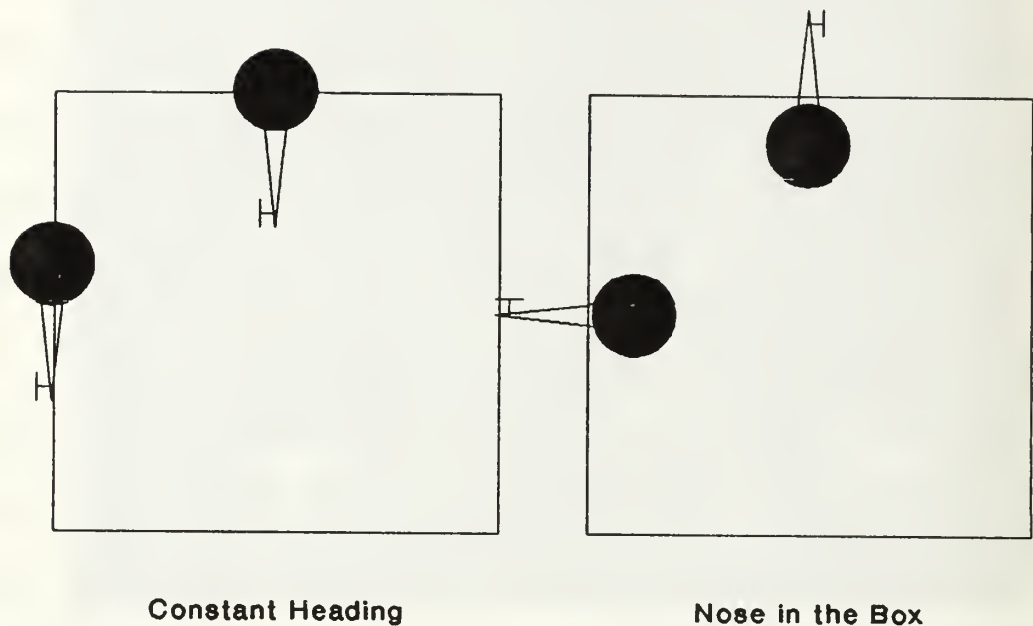


Figure 14. Box Patterns

D. HOVER VIBRATION TESTS

1. Equipment

Determining the type and sensitivity of accelerometers needed was the first step in the vibration data collection process. The vibrations anticipated were highly dynamic and small in magnitude. With this in mind, a very sensitive accelerometer was necessary. The accelerometer chosen, model 302B03, was built and supplied by PCB Piezotronics, Incorporated. It weighs only 1.4 ounces and can accurately handle

frequencies up to 5000 Hertz with very good resolution, and it has a sensitivity of 300mV/g. One single axis accelerometer, and a suitable power source with an amplifier, was purchased to be used for the first phase of the vibration testing. Two additional accelerometers will eventually be needed to provide simultaneous acceleration data in the vertical, longitudinal, and lateral directions. The power supply for the accelerometer weighs only 15 ounces; however, in its current configuration is too large for onboard use. The manufacturer can customize the power sources for the accelerometers into a single housing to minimize size.

The accelerometer was calibrated by the manufacturer; this calibration was confirmed at NPS by testing it on the Calidyne shaker table with a calibration accelerometer at several frequencies and amplitudes. The PCB accelerometer output was compared to the calibration accelerometer output through a Tektronix oscilloscope for observing attenuation as well as any phase shift.

Accurate measurement of rotor speed is fundamental to producing useful HHC data. For the hover tests, rotor speed is measured using a Skytach handheld tachometer which can be adjusted from 800 to 2250 rpm.

The output of the PCB accelerometer was initially sent to an oscilloscope where the frequencies and amplitudes of peak accelerations were manually recorded.

2. Procedure

At this point in the HHC program, vibration data collection was being done in hovering flight only. The data desired was vertical acceleration at the normal hover rotor speed and at various centerline locations along the RPH.

Accelerations were measured at four longitudinal stations on the *Legend*. The accelerometer was installed on a mounting block, which was then attached to the RPH. Power was supplied to excite the accelerometer through coaxial cable from the PCB power supply. The cable was secured to the RPH with plastic tie wraps to reduce the chance of becoming entangled in one of the rotors. Output, through coaxial cable, from the accelerometer was sent to the oscilloscope where it was

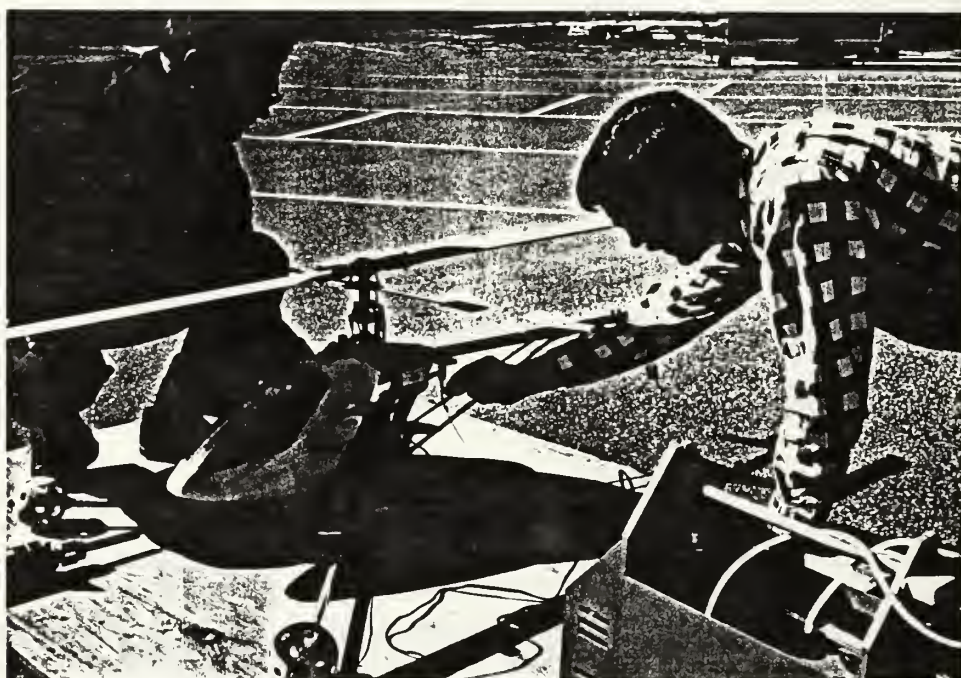


Figure 15. Legend with Vibration Testing Equipment

recorded along with the rotor speed as determined by the Skytach. In order to compare the accelerations at the various airframe stations, a fixed rotor speed was imperative. Figure 15 depicts the *Legend* with its associated vibration measuring equipment.

3. Vibration Data Results

A number of problems developed during the test set-up. First, rotor speed was measured with the Skytach rather than the General Radio Strobotac as originally planned, because the Strobotac's light source was "washed out" by ambient light during the initial tests. Secondly, the Tektronix 2245A oscilloscope used on the first tests displayed the RPH accelerations. Unfortunately, the oscilloscope displayed data of all frequencies and manually collecting it proved to be very difficult. A two channel recorder was then hooked up to the oscilloscope using a BNC tee fitting. The recorder and oscilloscope impedances apparently were not matched, thereby causing the accelerometer output to be altered as it was recorded, thus producing inaccurate results.

The data presented in Appendix B. was obtained using the oscilloscope and manual recording. This data shows the main rotor system is a major source of RPH vibration, just as it is on a full scale helicopter. The PCB 302B03 accelerometer performs as desired and will suit the long term needs of the HHC research project.

The oscilloscope proved not to be the best device on which to display the output of the accelerometer. The two channel recorder in its current configuration also lacked the accuracy needed. A spectrum analyzer was obtained that not only

can display the output of the accelerometer but also has a built in recorder that can store the data on a 3.5 inch computer disk and has the capability to output to a plotter. The data obtained using the two channel recorder, though inaccurate, did show that the spectrum analyzer could be used in RPH vibration testing. Time constraints in completing this thesis have precluded further vibration testing on the *Legend*; however, the Scientific Atlanta SD380 signal analyzer should meet the needs of the NPS flight test program for vibration testing.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The vibration data obtained from the initial flight tests was of limited value. However, the two bladed *Legend* appeared to produce peak accelerations at approximately twice the rotor speed. This indicates that like a full scale helicopter, the largest vibrations enter the airframe through the rotor system and not from other sources like the engine. The NPS HHC research effort can make great strides in advancing HHC if through its RPH flight program it can produce relative quantification of vibration levels and aircraft performance. Although the scaling factors between RPH's and full size helicopters may be difficult or even impossible to overcome, a relative comparison of vibrations and performance between unmodified, modified with HHC off, and modified with HHC on may provide enough information to warrant further study on full size helicopters.

The RPH flight operations conducted during this thesis research produced the first flights on both the *Heli-Star* and the *Legend*. During the incorporation of the RPH's into UAV program it became apparent that the "in house" knowledge was invaluable. And, the UAV Laboratory facility is a tremendous asset to NPS. Future research on helicopters will be possible because of the advances made in the flight operations portion of the HHC research. By building an RPH such as the *Legend* and maintaining all three remotely piloted helicopters, developing procedures for

measuring vibrations, and obtaining much of the equipment required for this, HHC research has been advanced. Additionally, a somewhat generic RPH program was introduced that can be used in other areas of helicopter research, including rotor blade design or various tail rotor configurations.

The possible benefits of HHC toward extending the life of aircraft by reducing airframe vibration levels as well as decreasing crew fatigue make the research effort worthwhile. When McDonnell Douglas Helicopter Company conducted their HHC research, they determined that vibrations in level flight were indeed reduced, yet on a maneuvering helicopter, the benefits were not as obvious. The reason for this, in part, is because the sensors and computers used may not have sensed, processed, and input needed changes fast enough. With the recent and continuing rapid advances in computer technology as well as the drive toward fly-by-wire flight control systems, the speed and complexity of an HHC system is not expected to be a limiting factor. Aircraft such as the SH-60B Seahawk which presently carry nearly four hundred pounds of passive vibration absorbers may also benefit by being modified to incorporate HHC, resulting in a weight savings as well as vibration reduction [Ref. 11].

The NPS HHC research has advanced through the completion of the flight operations intermediate milestone. Although the results of the vibration tests were less than satisfactory, needs were identified and more direction given toward the pursuit of obtaining accurate and appropriate data. The full benefit of this effort can only be seen if the RPH's continue to fly, in order to maintain pilot proficiency as

well as ensure the RPH's are serviceable. It is also necessary that the design of a data acquisition system proceed concurrently with the design and building of the HHC system.

B. RECOMMENDATIONS

The additional accelerometers and custom power source need to be obtained and tested. This can be done while a determination of whether an onboard flight data recorder or a telemetric data device would best suit the needs of the NPS HHC program. Perhaps the two-channel recorder previously unable to reproduce useable data can be easily modified through impedance matching and made to suit the needs of the HHC program. Ultimately, the completed data gathering system should be capable of measuring not only multi-axial accelerations but also rotor speed and airspeed. Baseline vibration and performance data need to be gathered on the *Bruiser* before its rotor system is modified to incorporate HHC.

Hover performance tests need to be conducted in order to determine if HHC can enhance aircraft performance through decreasing power required to hover. This is the aspect of HHC which is currently most debated. The McDonnell Douglas Helicopter Company tests were inconclusive on this point because the necessary performance parameters were not measured during their vibration testing.

Lastly, considering the scope of this research effort and its importance not only to the United States Navy but to all manufacturers and operators of helicopters, a joint research effort with another University interested in helicopter improvement

may be in order. The limited manpower that NPS has available for this program could be enhanced by including outside participants. The RPH facilities currently operational at NPS could attract the necessary participants. By forming a joint program, a fully operational HHC system could be flying much sooner than without such a program.

APPENDIX A: HELICOPTER OPERATIONS CHECKLISTS

HELICOPTER OPERATIONS DATA CARD

AIRCRAFT _____
PILOT _____

DATE _____
TIME _____

FLIGHT DATA

Takeoff Weight _____
Land Weight _____
Field Elevation _____
Engine Start _____
T/O _____
Land _____

METRO CONDITIONS

Field Elevation _____
Local Pressure _____
Pressure Altitude _____
Density Alt _____
Ambient Temp _____
Wind _____

CAUTION

FLIGHT OPERATIONS ARE LIMITED TO ABOUT 20 MINUTES
DUE TO FUEL CONSTRAINTS

TEST _____

COMMENTS

PACK-UP CHECKLIST

- _____ CHECKLISTS
- _____ TRANSMITTER BATTERIES CHARGED
- _____ RECEIVER BATTERIES CHARGED
- _____ AIRCRAFT
 - _____ Weight & Balance Completed
 - _____ Check Material Condition
 - _____ Access Covers Installed
- _____ TRAINING GEAR (if required)
- _____ FLIGHT BOX
 - _____ Fuel/Fuel Pump
 - _____ Starter
 - _____ Glow Plug Connector
- _____ STARTING BATTERY
- _____ TOOL KIT
 - _____ Kalt/UAV Tool Kits
 - _____ Chocks
- _____ CLEANERS
 - _____ Cleaning Fluid
 - _____ Towels/Rags
- _____ WALKIE/TALKIE'S
- _____ SOUND ATTENUATORS
- _____ FIRE EXTINGUISHER
- _____ DATA GATHERING EQUIPMENT
 - _____ Stopwatch
 - _____ Data Sheets/Test Procedures
 - _____ Paper & Pencil
 - _____ Camera/Video Equipment

PRE-FLIGHT CHECKLIST

Weight & Balance	Complete
Fire Extinguisher	Available
All Switches	Off
General Condition	Check Check for leaks, missing panels, level attitude, etc.
Nose Area	Check Ensure servo tray, gyro, & battery pack are installed and secure
Rotorhead/blades	Check Check security of nuts and bolts, inspect blades for cuts and de-lamination, ensure controls do not bind or chaff
Fuselage Area/Engine	Check Check security of nuts and bolts, ensure fuel tank and cooling shroud are secure
Fuselage	Install
Landing Gear	Secure
Tailboom	Check Check security of boom, vertical and horizontal surfaces, ensure controls do not bind
Tailrotor	Check Check security of nuts and bolts, inspect blades for cuts and de-lamination, ensure controls do not bind or chaff

START CHECKLIST

Surrounding Area	Clear
Fuel	Full
Receiver & Gyro	On
Transmitter	On
Control Response	Check
Radio Range	Check
Glow Plug	Hot
Mainrotor Blades	Secure
Starter	Engage
Equipment	Remove
Glow Plug Connector	
Starter	
Flight box	
Starter Battery	
Engine Speed	Idle
Time	Record

CAUTION

FLIGHT OPERATIONS ARE LIMITED TO ABOUT 20 MINUTES
DUE TO FUEL CONSTRAINTS

TAKEOFF CHECKLIST

T/O Clearance	Received
Area	Clear
Controls	Check
Fuel Quantity	Note
Engine	Advance Throttle
Time	Record

CAUTION

FLIGHT OPERATIONS ARE LIMITED TO ABOUT 20 MINUTES
DUE TO FUEL CONSTRAINTS

LANDING & SHUTDOWN CHECKLIST

Clearance	Received
Landing Area	Clear
Landing	As necessary
Engine	Idle
Time	Record
Fuel Control	Shut off
Blades	Completely stopped
All Switches	Off

POST-FLIGHT CHECKLIST

- | | |
|--|---------|
| All Switches | Off |
| Aircraft | Defuel |
| General Condition | Check |
| Check for leaks, missing panels,
level attitude, etc. while cleaning | |
| Nose Area | Check |
| Ensure servo tray, gyro, &
battery pack are installed
and secure | |
| Rotorhead/blades | Check |
| Check security of nuts and bolts,
inspect blades for cuts and
de-lamination, ensure controls do
not bind or chaff | |
| Fuselage Area/Engine | Check |
| Check security of nuts and bolts,
ensure fuel tank and cooling
shroud are secure | |
| Fuselage | Install |
| Landing Gear | Secure |
| Tailboom | Check |
| Check security of boom,
vertical and horizontal surfaces,
ensure controls do not bind | |
| Tailrotor | Check |
| Check security of nuts and bolts,
inspect blades for cuts and
de-lamination, ensure controls do
not bind or chaff | |

APPENDIX B: VIBRATION DATA

GMP Legend

March 7, 1991

Station Designation:

Fuselage On: Tip of Fuselage is 0.0
Overall Length: End of Tail Rotor Assemble is 51 inches

<u>Station</u>	<u>Position</u>	<u>Description</u>
1	11.75"	Center of forward landing gear strut
2	17.56"	Center of aft landing gear strut
3	22.88"	Forward section of tail boom
4	31.50"	Center section of tail boom
5	44.25"	Aft section of tail boom

Gear Ratios:

Weight:

Engine to Main Rotor: 8.60 to 1	Dry: 10.29 lbs.
Tail rotor to Main Rotor: 4.75 to 1	Wet: 10.83 lbs.

RPM	O/P Freq (Hz)	O/P Amp (g)	Station, Throttle Setting, & Rotor Speed
1080	39.8	13.3	3, idle, 18 Hz
1570	39.8	23.3	3, hover, 26.2 Hz
985	31.8	20.0	4, idle, 16.4 Hz
1320	39.8	20.0	4, hover, 22 Hz
1025	unk	16.7	5, idle, 17.1 Hz
1300	31.8	16.7	5, hover, 21.7 Hz
1080	22.7	20.0	5 (w/ training wheels), idle, 18 Hz
1570	39.8	20.0	5 (w/ training wheels), hover, 26.2 Hz
1100	45.2	20.0	2 (w/ training wheels), idle, 18.3 Hz
1580	39.8	20.0	2 (w/ training wheels), hover, 26.3 Hz

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